ESLÉ

Technical Note

1968-36

E. Stern

Microsound Components, Circuits, and Applications

30 October 1968

Lincoln Laboratory

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Lexington, Massachusetts

AD680786

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

LINCOLN LABORATORY

MICROSOUND COMPONENTS, CIRCUITS, AND APPLICATIONS

ERNEST STERN

Group 46

TECHNICAL NOTE 1968-36

30 OCTOBER 1968

LEXINGTON   MASSACHUSETTS

ABSTRACT

Acoustic analogs of conventional microwave transmission line (microsound) components on the surface of crystalline substrates should find application in wideband, high-capacity signal and data processors.

These microsound transmission lines, hybrids, and couplers interconnect microsound transducers, amplifiers, isolators, and phase shifters to form microsound circuits capable of autocorrelation, Fourier transformation, and matrix permutation functions.

Compatible component configurations are proposed and evaluated which perform the basic functions of wave guidance, amplification, isolation, and transduction. The anticipated difficulties with their realization is discussed, and the status of critical problems, including the epitaxial growth of acoustic thin films and sub-micron etching procedures, will be given. Several circuits capable of autocorrelation, cross correlation, Fourier transformation, and matrix permutation are described.

CONTENTS

MICROSOUND COMPONENTS, CIRCUITS, AND APPLICATIONS

I. INTRODUCTION

During the past decade, an increasing amount of research and development has been directed toward the realization of wideband acoustic components. These efforts have produced a large volume of papers on the subject in the applied physics and engineering journals and at acoustic and solid-state microwave device conferences.

There are now more than one hundred highly trained researchers working on the various bottlenecks hindering the realization of the desired components. An effort of this magnitude costs our nation between five and ten million dollars per year for this applied research. Why is there this intense interest in wideband acoustic phenomena and components? Why have several score researchers tied their careers to the fortunes of acoustic devices? The answer lies partly with the needs of modern signal and data processing systems and with the unique properties of the sound waves themselves.

The exigencies of modern warfare require the acquisition and processing of immense quantities of data in very short periods of time. Perhaps the most demanding military problem is associated with antiballistic missile radar sensors in which the available information consisting of hundreds of thousands of microwave echoes with large bandwidths has to be processed in a few minutes. These sensors probably require delay-line systems with a bandwidth-delay time product perhaps as large as 10^6.

The cost of computer memory has decreased with the size, bandwidth, and operating time of the individual components. Long wideband delay lines with fast access time may contribute to the cost reduction of special purpose computers.

The utility of sound for these applications in solids is related to the low propagation velocity and the excellent transmission characteristics of acoustic media. Sound travels five orders of magnitude more slowly than electromagnetic waves. It is possible to store a signal within one centimeter of crystal which ordinarily requires a 1-kilometer long air-filled transmission line. The high Q of acoustic media permits acoustic delay times perhaps one hundred times that feasible with low-loss electromagnetic waveguide. Also, the wave-like nature of the sound permits the effective use of gratings and transducer arrays for achieving such special signal processing circuits as pulse compressors and auto-correlators.

At this point, it should be made clear that this discussion is restricted to high-capacity signal processing and data processing components whose bandwidth exceeds 100 MHz, and to those phenomena in which the signal energy is acoustic and not in some other form as optical, spin-wave, or electrical disturbances. The latter restriction has been imposed because it is believed that it is possible to achieve simpler and more effective acoustic counterparts to the magneto-acoustic[1] and acousto-optic[2] devices.

Most of the effort until recently has been associated with realizing bulk acoustic wave components and, in particular, nondispersive[3] and dispersive[4] delay lines and bulk acoustic wave amplifiers.[5] The typical bulk wave device consists of a crystalline block (Fig. 1) to which opposing piezoelectric transducers are attached. The piezoelectric transducer emits a narrow beam of acoustic energy into the material. If the crystal is a piezoelectric semiconductor, then the presence of conduction electrons and an accelerating electric field may amplify[5] the acoustic wave.
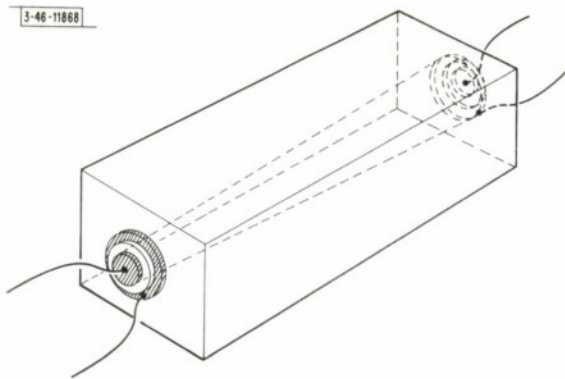
Fig. 1. Typical bulk wave device.

Fig. 2. Surface wave wedge transducer. Most of the shear wave energy is reflected at the interface and absorbed; a small portion is coupled to a Rayleigh wave.

Fig. 3. Rayleigh wave comb transducer. The comb teeth are separated a Rayleigh wavelength. The longitudinal wave energy in the comb teeth is coupled to two Rayleigh waves propagating to right and left, and to a longitudinal wave into the substrate.

Fig. 4. Interdigital transducers on a piezoelectric block.

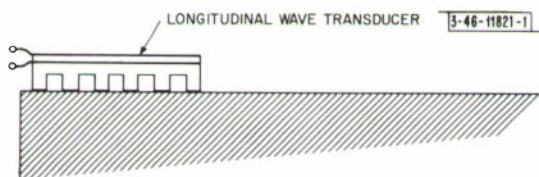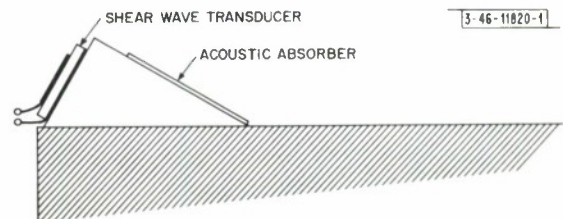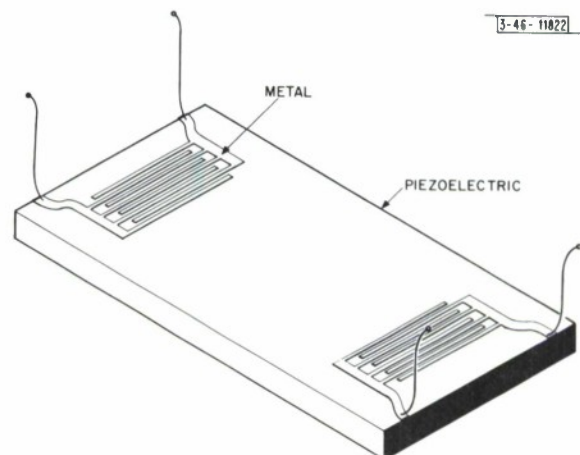Bulk devices have several features in common. They have input and output tranducers which convert the electrical signal to acoustic energy. The acoustic energy is beamed through the medium from the input to the output transducer. In all bulk devices it is almost impossible to tap, switch, vary the delay, vary the amplitude, or otherwise manipulate the acoustic energy during transit. Consequently, applications have been restricted in the main to passive dispersive and nondispersive delay lines, and where the manipulation is done with electronic circuits.

It is also possible to propagate sound on the surface of crystals; such a disturbance is called a Rayleigh[6] wave. The physical difference between a bulk and a surface wave is small; the technological difference is very large indeed, because the acoustic signal is accessible for manipulation throughout its path. The subject matter of this paper is the exploitation of this difference. The wave-like character of the surface disturbance permits the utilization of waveguides and a host of associated components and techniques heretofore restricted to microwave circuits. Such waveguides can transmit the acoustic signal to the components which transduce, amplify, delay, and isolate the signal.

It is proposed that these sound wave analogs of microwave components and circuits be called microsound components and circuits.

The discussion that follows contains a description of the four basic microsound components as they exist today, followed by a description of how the transducer, isolator, amplifier, and waveguide may look within a year or two as a result of the efforts presently under way. Several circuits will be described which perform the signal processing functions of delay, Fourier transformation, and matrix permutation, followed by a discussion of the anticipated difficulties which block the realization of these microsound circuits.

II. SURFACE WAVE COMPONENTS

Rayleigh waves, in contrast to bulk waves, are localized to the surface of solids. The typical particle motion is retrograde elliptical, and the amplitude decays exponentially into the body of the medium. The phase velocity of the Rayleigh wave is about 95 percent of the bulk shear wave velocity in most media. Particle displacements are miniscule; a typical displacement is a fraction of an angstrom. At UHF frequencies the wavelengths are comparable to optical wavelengths (several microns at 1 GHz).

These surface acoustic waves were first described by Lord Rayleigh. At low frequencies, such waves are generated with the wedge transducer shown in Fig. 2. Here, the shear wave in the wedge is mostly reflected at the interface and absorbed, and a small portion of the energy is refracted as a surface wave on the substrate. The comb transducer[7] (Fig. 3), an improvement over the wedge, has teeth one Rayleigh wavelength apart. The incident longitudinal waves couple to a standing surface wave on the substrate, which radiates into the bulk and in opposite directions on the surface. The conversion loss is quite large, and at frequencies in the GHz range the wavelengths are on the order of 3 microns, or 1.2×10^{-4} inches. Teeth of that size would be difficult to fabricate and, because of their size, would be very fragile.

The interdigital transducer[8] shown in Fig. 4 was developed for use on piezoelectric substrates. The signal leads are connected to the terminals of the transducer, and the adjacent fingers are located one-half acoustic wavelength apart. The alternating signal voltage interacts with the piezoelectric substrate and produces an acoustic standing wave. If the transducer consists of n evenly spaced finger pairs, the transducer is n wavelengths long. A null in radiation is obtained at frequencies where the transducer is $n + \frac{1}{2}$ wavelengths long. Consequently,
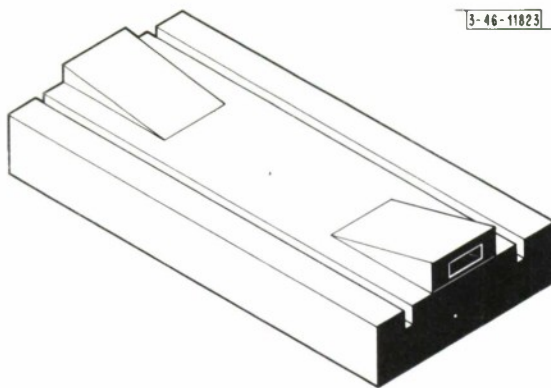
Fig. 5. Slot transmission line. The insertion loss between widely separated wedge transducers decreases dramatically when slots deeper than a Rayleigh wavelength are inscribed.

Fig. 6. Overlay transmission lines. The phase velocity in the slow medium is less than in the fast medium.

"SLOW" ON "FAST" ACOUSTIC MEOIUM

"FAST" ON "SLOW" ACOUSTIC MEDIUM

INTERDIGITAL TRANSDUCERS

LIGHT

METAL

CAOMIUM SULPHIDE

Fig. 7. Surface wave amplifier on block of CdS. Gain is obtained when the light produces carriers in high-resistivity CdS which are accelerated to a drift velocity in excess of the Rayleigh wave velocity by the electron field.

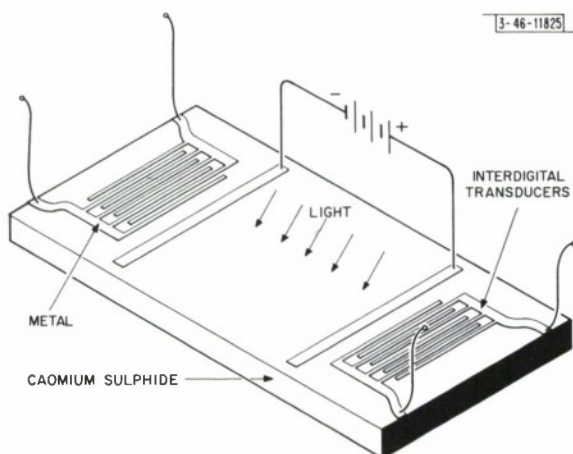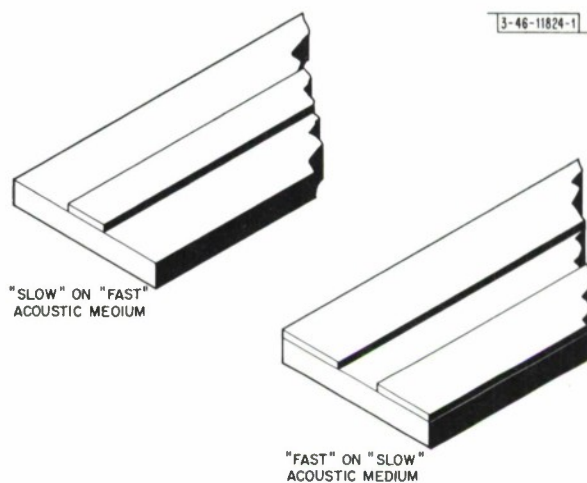the fractional bandwidth is equal to $1/n$. This transducer has found wide application in laboratories because it is simple to fabricate and efficient. For example,[9] bandwidths in excess of 30 percent and conversion losses of less than 4 dB, of which 3 dB is caused by the bidirectivity of the device, have been realized with five finger-pairs at 100 MHz. Also, 1-GHz operation[10] has been achieved, but with reduced efficiency.

One-MHz surface acoustic waves have been guided by a pair of grooves[11] as shown in Fig. 5. The two wedge transducers were placed far apart on a metal substrate. A 1-MHz signal was transmitted from one to the other and the insertion loss noted. Then the two grooves were inscribed and the loss dropped 10 dB. The reduction of loss was attributed to wave guidance. Another form of waveguide, an acoustic analog of the dielectric microwave guide, is shown in Fig. 6(a). It consists of a dense material,[12] which is acoustically slow, deposited onto a faster acoustic substrate. The acoustic energy is bound to the vicinity of the overlay, and it follows the guide around gradual bends. Another version of this transmission line[13] is a slot cut into a fast overlay on a slower substrate [(Fig. 6(b)]. In these structures, nearby transmission lines are loosely coupled to each other, making feasible such devices as directional couplers.[12,14]

The bulk acoustic wave amplification mechanisms[15] found in a piezoelectric semiconductor have been adapted to surface acoustic waves[16] (Fig. 7). Here a surface acoustic wave is generated on a surface of the high resistivity cadmium sulfide crystal, a piezoelectric semiconductor. Electrodes are deposited athwart the acoustic beam, and optically pumped conduction electrons are accelerated with the applied electric field. Amplification is obtained when the electron drift velocity exceeds the velocity of the surface acoustic wave. This amplifier has limitations that are similar to those of the bulk wave amplifier in that the substrate must incorporate the three qualities of acoustic conduction, piezoelectric transduction, and semiconduction. For example, CdS is a particularly good piezoelectric material, and it is a very poor acoustic and semiconducting medium at UHF.

III. MICROSOUND COMPONENTS

Suppose that, for the moment, we hold in abeyance our critical faculties and consider what microsound components might look like if we ignore the limitations of present-day technology.

The losses found in acoustic media generally increase with frequency. For example, metals are lossy above a few MHz, ceramics above a few tens of MHz, and only certain nonconducting single crystals exhibit low losses in the frequency range from 500 to 5000 MHz. Suppose that it is possible to obtain epitaxial overlays of one low-loss acoustic medium onto another. At 1 GHz a typical wavelength is about 3 microns. Consequently, the principal cross-sectional dimensions of a waveguide are on that order, and if the waveguide is to perform well, these dimensions should be held to a tolerance of a small fraction of one micron. Since the diffraction limit of light is on that order, conventional photo-resist methods cannot be used, and a new technique must be employed. These techniques are described in Sec. V.

A. Transmission Line Components

A microsound analog of a microwave transmission line and filter network, shown schematically in Fig. 8, contains sections of transmission line that act as coupled cavity resonators in the filter network. The surface acoustic wave energy is bound to the vicinity of the overlaid waveguide. The transmission-line discontinuities, which establish the limits of the resonators, are designed to reflect energy only in the fundamental transmission-line mode, and do not scatter energy into body waves or higher-order waveguide modes.
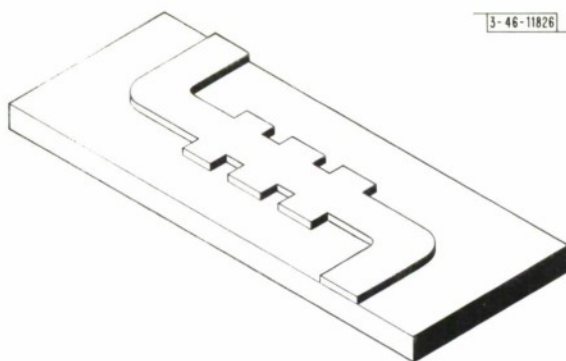
Fig. 8. Microsound transmission line, bends, and filter. The dimensions of the lines at 1 GHz are about 2 microns wide, 1 micron high, with an edge definition of ± 0.05 micron.

Fig. 9. Directional and hybrid couplers. Energy into 1 goes mostly to 2, and a small portion is coupled to 3. If the flow is reversed (from 2 to 1), energy is coupled to 4. Energy into hybrid terminal 2 emerges from 5 and 6 equal in amplitude and 90° out of phase. Two equal signals 90° out of phase emerge at 2; if the phase relationship is reversed (−90°), the energy emerges at 7.
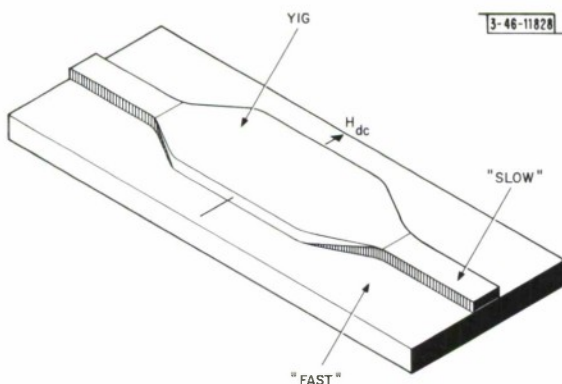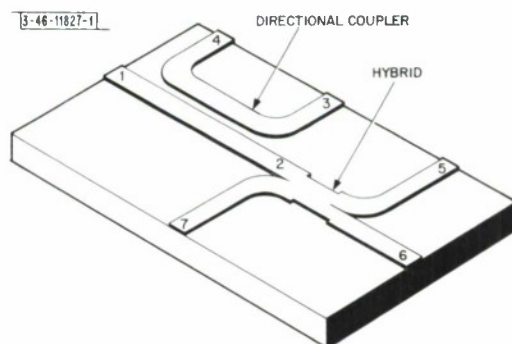
Fig. 10. Magneto-acoustic isolator or phase shifter. At the surface of YIG in a microscopic region, the particle motion in a plane perpendicular to H_{dc} approximates the motion of an elliptically polarized shear wave. Since positive rotation couples more strongly to the spin wave manifold than negative, nonreciprocal transmission characteristics are anticipated.

Fig. 11. Microsound double-pole double-throw switch. Power into 1 and 2 exits at 3 and 4, respectively. If the field H_{dc} is reversed, the power emerges at 4 and 3.
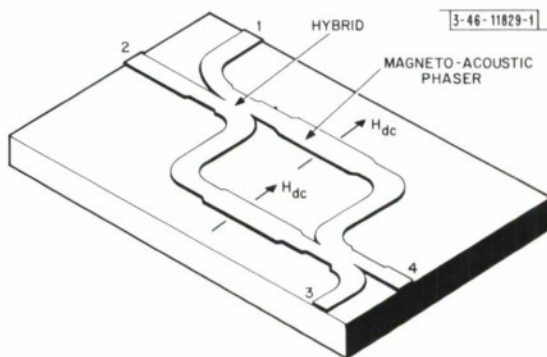
Suppose that most of the energy is contained within an acoustic wavelength on either side of of the overlay region and the velocity of sound in the guide is v_g. If the transmission line is curved at a radius r, then the acoustic energy a wavelength away and on the outside of the curve propagates at a velocity $v_m(1 + \lambda/r)$. If this peripheral velocity exceeds the surface wave velocity of the substrate v_s, then the peripheral energy continues to propagate in the initial direction and is lost to the transmission line. Consequently, the radius of curvature must be larger than $\lambda/(v_s/v_m - 1)$. It is desirable to have a small radius of curvature for many applications and, in those instances, the ratio v_s/v_m should be as large as possible. For example, an epitaxial layer of zinc oxide, a particularly slow medium, on a substrate of beryllium oxide, a particularly fast medium, would meet these requirements very well.

The directional coupler in Fig. 9 couples a small portion of the energy traveling from 1 to 2 into terminal arm 3. If the energy flow is reversed (from 2 to 1), the coupled sample appears at 4. A low-frequency version of the coupler[12] has been demonstrated at 10 MHz with gold overlay on fused quartz.

Energy into terminal 2 of the hybrid coupler is divided equally between 5 and 6, and the signal in 6 lags by 90° the energy in 5. The device is reciprocal; two signals of equal amplitude and 90° out of phase emerge at 2. If the phase relationship between 5 and 6 is reversed, the signal emerges at 7. These characteristics can be used to fashion a switch if a means is employed to reverse the phase of the signals into ports 5 and 6. Some of the features of the hybrid coupler have been demonstrated[14] with a grooved guide at 1 MHz.

B. Isolator, Switch, and Gyrator

The nonreciprocal interactions of circularly polarized body shear waves with spin waves[17, 18] may be adaptable to surface acoustic waves. If the surface disturbances are viewed in a direction lying in the plane of the surface and perpendicular to the propagation, then the particle motion is elliptical retrograde. This is a fairly close approximation to the particle motion of a circularly polarized shear wave.

A transmission line made of a magneto-acoustic material such as yttrium iron garnet and magnetized to the magneto-acoustic crossover point by a field lying in the plane of the surface and normal to the propagating direction (Fig. 10) should exhibit greater insertion loss to a wave propagating to the left than to a wave propagating to the right. This effect can be used to minimize the effects of multiple reflection in the transmission line. It should also be feasible to make nonreciprocal phase shifters with the same structure. Here, the phase shift of signals traveling from left to right differs from the phase shift of signals traveling from right to left. If this difference is 90°, a switch circuit becomes feasible (Fig. 11); the energy into 1 emerges at 3, and if the field directions are reversed, energy in 1 emerges at 4. Energy into 2 emerges at the complimentary ports.

Reciprocal phasers may be feasible with piezoelectric transmission lines, since the phase velocity of sound in piezoelectrics is related to the sense and to the direction of the electric stress. Such phasers are similarly suited to the construction of switches.

C. Amplifiers

A wave propagating on the surface of a piezoelectric medium may have dipolar electric fields[19] that extend out of the surface for a distance of about one wavelength. The electric fields could, in principle, penetrate into a semiconducting layer and interact with the conduction electrons.[20] The amplifier mechanism has been analyzed,[21] and a working model with 20-dB

PIEZOELECTRIC
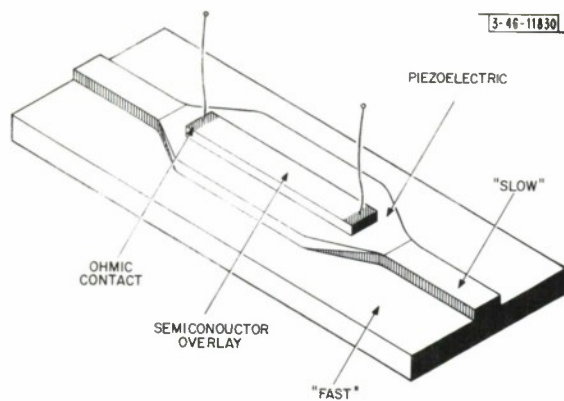
"SLOW"

OHMIC
CONTACT

SEMICONDUCTOR
OVERLAY

"FAST"

Fig 12. Microsound amplifier. The acoustic energy in the piezoelectric produces electric fields which extend out of the surface and into the semiconductor, where they couple to the carriers.

$(n+\frac{1}{4})\lambda$

"SLOW"

ABSORBER

PIEZOELECTRIC
FILM

"FAST"
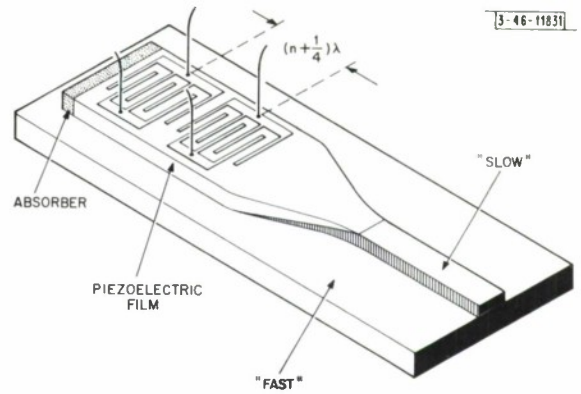
Fig. 13. Microsound **directional transducer.** Two bidirectional transducers are separated one quarter wavelength and driven in phase quadrature to obtain radiation in one direction only.

WORD
INPUT

CLOCK

AND

OR

MICROMINIATURE
ELECTRONIC CIRCUIT

FILTER AND AMPLIFIER
RESONANT RING
OSCILLATOR

DIRECTIONAL
COUPLERS

SWITCHES

TERMINATIONS

MICROSOUND CIRCUIT

TRANSDUCERS
AND DETECTORS

Fig. 14. Microsound parallel digital delay lines. The resonant ring oscillator provides the carrier for the base-band digital impulses. Data are processed and recirculated by the microminiature electronic circuitry.

electronic, 6-dB net gain has been obtained at 100 MHz.[22] A microsound version of this amplifier is shown in Fig. 12. The ac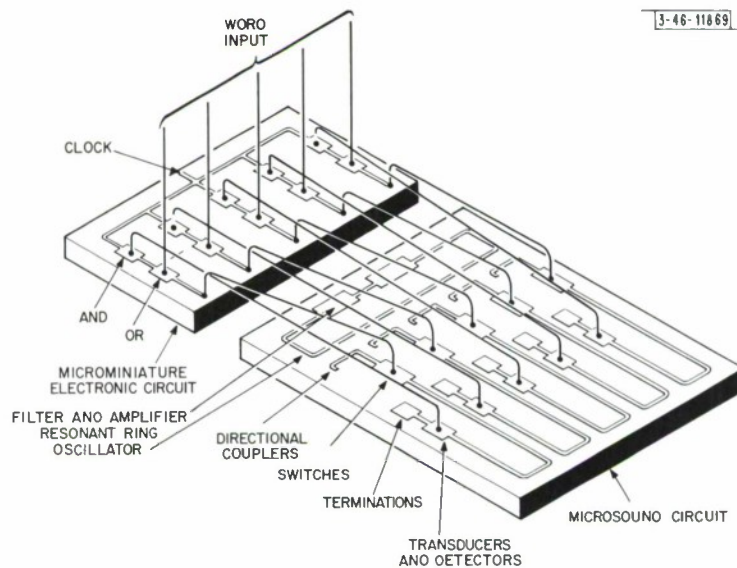oustic energy in the waveguide is radiated into the piezoelectric pad, where the electric field associated with the wave penetrates into the overlayer of semiconductor. Carriers in the semiconductor interact with the applied DC and microsound electric fields. The conduction carriers drift in the direction of the electric field, which is parallel to the sound wave propagation direction. If the drift velocity of the carriers exceeds that of the sound wave, electronic gain is obtained.

In a bulk wave amplifier, it is necessary to use a piezoelectric semiconductor such as cadmium sulfide. These materials have relatively low mobilities and high acoustic losses at frequencies above 1 GHz. Consequently, it is necessary to apply very large voltages to overcome the low mobility and, since a considerable amount of acoustic energy is absorbed, the net gain of the amplifier is also reduced. Because of the relatively low mobility and requisite high electron density, a considerable amount of DC dissipation occurs in the crystal, and suitable amplifiers have worked only in a pulsed mode at UHF frequencies because of extreme heating of the crystals. In the composite amplifier, it is possible to select a low-loss, crystalline piezoelectric substrate with a high piezoelectric coupling constant such as lithium niobate and a semiconductor overlay with high mobility. In this way, it is possible to optimize the piezoelectric and the semiconducting components of the amplifier independently. A considerable improvement in amplifier performance should be obtainable by this strategy. Obtaining semiconducting surfaces of high mobility presents a special problem and may require extensive investigation of surface and interface properties of semiconductors.

D. Transducer

The transducer in Fig. 13 consists of a piezoelectric overlay and a metallized interdigital structure. A suitable matching structure is inserted between the piezoelectric pad and the waveguide. This transducer[23] is directional — the two sections are driven in phase quadrature and are located one quarter wavelength apart. Constructive interference in the desired direction and destructive interference in the opposite direction are obtained by this configuration.

IV. APPLICATIONS

The microsound components can be interconnected to form specialized circuits for signal and data processing applications. One example is the parallel delay line[24] (Fig. 14) for digital computer applications. The circuit satisfies the need for precisely matched parallel delay lines which are compatible with digital computer circuits in which the bits in a word travel on parallel paths, and the bits in each time frame constitute a word. Also, it is desirable to provide fast access time to the stored information in these high-capacity delay lines. The access time could be reduced at will by using microsound couplers (not shown) along the microsound delay line.

Matched digital delay lines require delay times which are equal within one time frame. It has not been feasible to construct bulk delay lines with this precision and, as a result, parallel delay lines are not ordinarily employed for memory applications. With microsound circuits, precise matching is feasible because the lines are accessible for trimming operations. In the figure, the resonant ring oscillator generates UHF acoustic energy which is distributed to the delay lines via the directional couplers. The electrical control signal opens the switch modulators, and pulses of acoustic signals propagate along the line. The acoustic signals are transduced and detected at the tap points. The detected electrical signals are processed by the
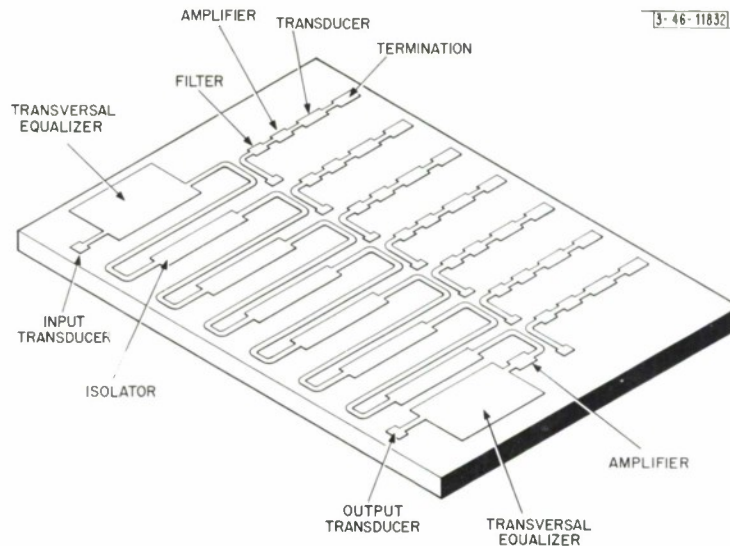
Fig. 15.   Microsound tapped delay line circuit.   The transversal equalizer compensates for the dispersion and errors in the delay line, and the isolators suppress reflections.   The directional couplers sample the energy at the tap points; the filters could be set for autocorrelation purposes.
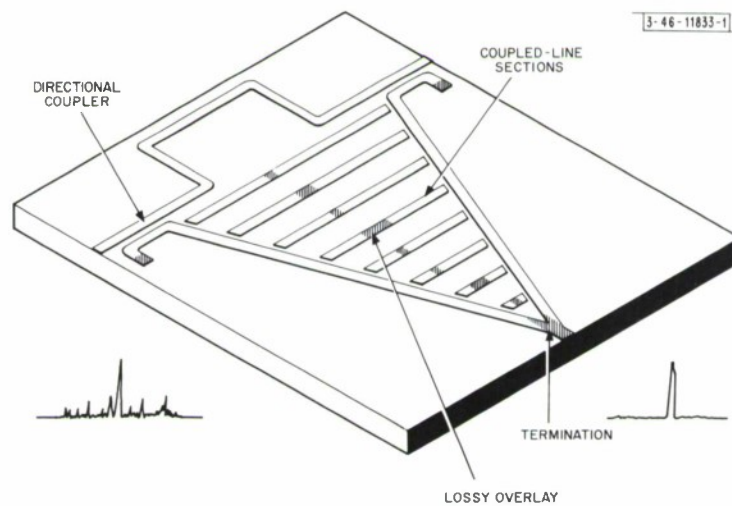

Fig. 16.   Microsound transversal equalizer.   The circuit provides the means to eliminate time sidelobes by destructive interference at the output coupler.

10

microelectronic circuitry. The microelectronic circuits are compatible with the microsound circuit structures. If it is desirable, both circuits could be deposited on the same substrate.

Another example of how the microsound components can be interconnected is a tapped delay line (Fig. 15). The electrical signal is converted to microsound with a suitable transducer; the acoustic signal is passed through a transversal equalizer which compensates for the residual dispersion of the transmission-line components. Reflections and resonances are suppressed by the microsound isolators. The main signal energy in the transmission line is delayed, amplified, and converted to an electrical signal which, in turn, could connect to another tapped delay line. Samples of the signal may be obtained with directional couplers that couple a small portion of the main line signal to a tap which, in turn, might consist of a filter network, an amplifier, and a transducer.

The amount of delay obtained by these means is limited principally by the size of the substrate, by the permissible radius of curvature in the transmission line, and by the limitations of the available etching technology.

The transversal equalizer (Fig. 16), a simple ladder structure, is used to compensate for the dispersion and the errors in the transmission lines. The equalizer is used to correct for one effect of delay line error, which is to transfer energy into the time sidelobes of short impulses. The distorted impulse is fed into the line on the left and is suitably delayed along the upper pathway. A portion of the pulse is coupled into the ladder structure below. Each one of the rungs provides a suitable amplitude and phase adjustment to the signal which coincides with a particular time sidelobe at the output end of the equalizer. The corrective signals destructively interfere with the unwanted time sidelobes of the impulse.

Another application of microsound is the Fourier transformer of Fig. 17. It is a Blass[25] array, which is capable of forming over a relatively wide bandwidth the Fourier transform of a signal. The array consists of equally spaced, concentric transmission lines and an overlay of radial transmission lines with a directional coupler at each crossover. The inputs are connected to the concentric lines, and the outputs emerge at the ends of the radial lines. If the radial line is at an angle of one radian, then the distance from the output to every input terminal is the same, and the coupled signals will arrive at all inputs at exactly the same instant of time. The converse is also true; if a signal is injected into all inputs at the same instant (or the same phase), then most of the energy will appear at output 1. Suppose energy is put into output Θ_1. The path-length
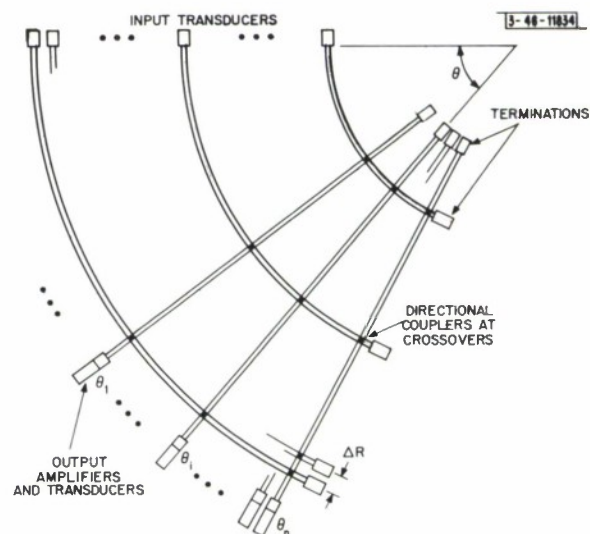

Fig. 17. Microsound Blass array. The circuit is a transmission-line approximation to an optical lens in that it yields the Fourier transform components at the output of the time-dependent signal samples at the input.

difference to adjacent inputs is equal to $\Delta R(\Theta_1 - 1)$, where ΔR is the difference in radius between adjacent concentric lines, and Θ_1 is the angle of the radial line. The reciprocal condition also applies; if the inputs are sequentially delayed by an amount produced by a line length ΔR $(\Theta - 1)$, then most of the energy will emerge at the Θ_1 output.

Suppose the input signals are obtained from the taps of an equally spaced delay line with a delay of τ seconds between taps. If the delayed sinusoidal signal frequency $\omega_o = 2\pi n/\tau$ rad/sec (n is an integer), then all the tapped signals are in phase and the signal emerges from output 1. If $\omega = \omega_o + \Delta\omega_1$, where $\Delta\omega_1 = k_a \Delta R(\Theta_1 - 1)/\tau$, and k_a is the propagation constant of the transmission line in the Blass array, then most of the signal emerges at output Θ_1. Similarly, other frequency components of the signal will coalesce at output terminal Θ_i, as defined by the equation $\Theta_i = 1 + \Delta\omega_i\tau/k_a\Delta R$. The outputs constitute the Fourier components of the signal. The converse is also true; the signal will emerge from the delay line if the Fourier components are injected into the outputs.

The delay line in Fig. 15 and the Blass array in Fig. 17 could be combined to produce the microsound correlator (Fig. 18). If the phase shifts are set to zero and the gain of all the amplifiers is set to the same value, the circuit behaves as a Fourier transformer or autocorrelator. If a second circuit is used to form the Fourier transform of $f_2(t)$, and if the phase and amplitude of the output phasers and amplifiers are set to the conjugate of the Fourier transform $F_2^*(\omega)$, then the outputs are the product $F_1(\omega) \times F_2^*(\omega)$. The inverse transform produces the cross-correlation function of two independent signals.
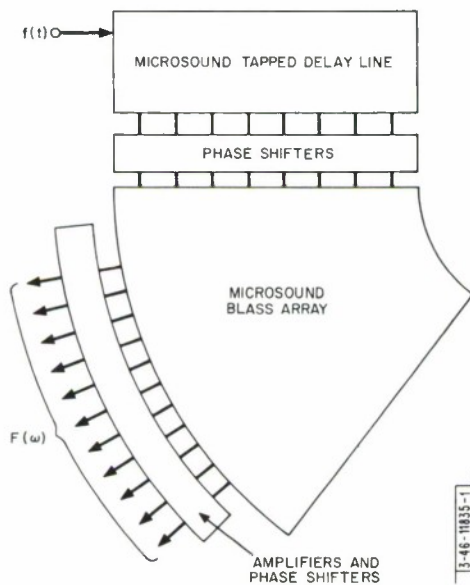

Fig. 18. Microsound correlator circuit.

If a phase slope is inserted into the input phasers, a signal of a particular frequency can be made to emerge at any output. It is possible to form a multi-throw switch by these means, or to tune a spectrum analyzer to a different portion of the spectrum.

Signal-switching matrices are also feasible through the utilization of phasers and couplers. Such circuits could perform matrix permutation, variable signal delay, and the like. For example, the circuit shown in Fig. 19 performs the function of variable delay. The input signal is routed either through the shorter lower pathway or through the longer upper pathway. By selecting
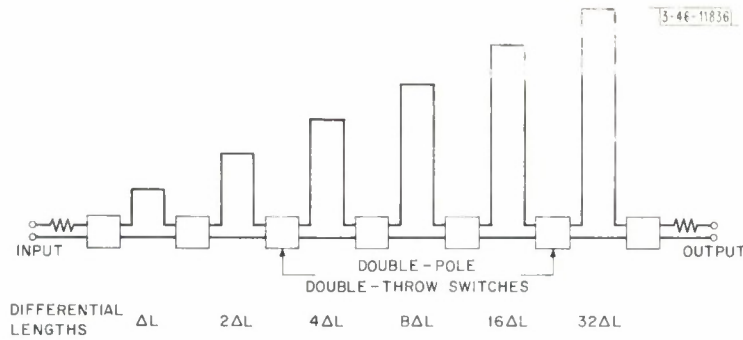
Fig. 19. Schematic diagram of a digital microsound variable time delay circuit.

the routing, it is possible to establish a differential delay path ranging from 0 to $63\,\Delta L$ in incremental steps of ΔL.

These circuits are examples of what may be done with microsound components. Many other applications are possible which require the small size, high storage capacity, ready access, and flexibility of microsound circuits.

V. PROBLEMS

The realization of microsound components in the frequency range from 500 to 5000 MHz is limited by a number of considerations which include problems with design, manufacture, and measurement.

High-frequency components should be built with epitaxial films of piezoelectric, semiconducting, and magnetoacoustic materials on low-loss crystalline substrates. A particular example of such a film is the YIG film on YAG substrates[26] (Fig. 20). This example is particularly noteworthy because it represents an achievement that goes beyond the complexities of depositing simpler materials as Z_nO, B_eO, and G_e on suitable substrates. This technology should be employable to make new combinations of materials such as zinc oxide films on B_eO or S_i on Z_nO.
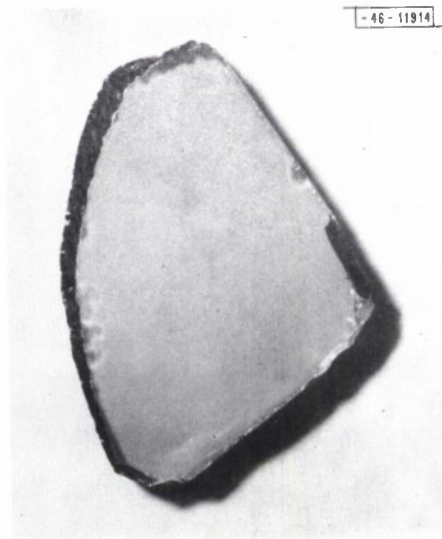

Fig. 20. Two-micron epitaxial layer of yttrium iron garnet on single crystal yttrium aluminum garnet. (Courtesy of George Pulliam)
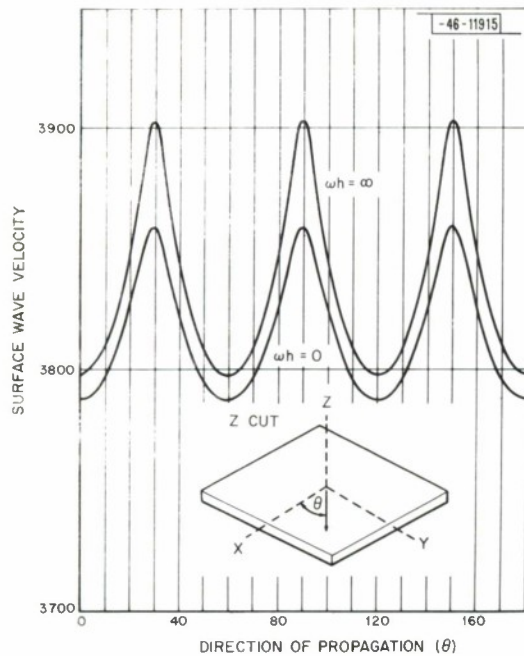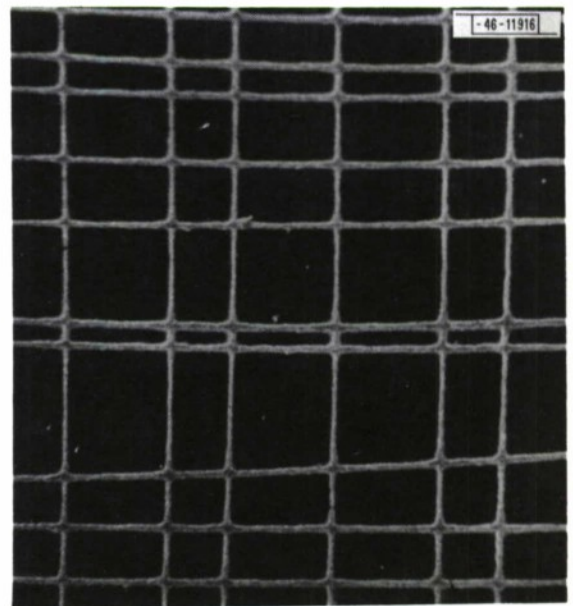
Fig. 21. Surface wave velocity vs propagation direction on z-cut lithium niobate. (Courtesy of W. R. Jones)

Fig. 22. Quarter-micron wires separated by as little as a quarter micron. Made by exposing photo-resist with a scanning electron microscope beam and by etching the gold with a DC ion beam. (Courtesy of A. N. Broers)

14

Detailed analysis of surface waves on various crystalline materials and combinations of materials is desired. An example of the kind of analysis that is needed are the phase velocity graphs[27] as a function of direction on lithium niobate (Fig. 21). Without precise knowledge of the propagation constants of the materials (and the dominant mode in the waveguide), such elaborate waveguide circuits as the Blass array of Fig. 16 would not be feasible.

Photo-etching methods are limited by light diffraction to an accuracy of about $\frac{1}{2}$ micron. This restricts the operating frequency of microsound components to less than several hundred MHz. New techniques are required which yield precision at least one order of magnitude greater than obtainable with photo-etching methods if components in the GHz frequency range are to be achieved. Electron beam etching methods should provide this precision. One notable achievement in this area is the grid of wires $\frac{1}{4}$ micron wide and on $\frac{1}{4}$-micron centers produced with the aid of a scanning electron beam microscope by A. N. Broers[28] (Fig. 22).

VI. CONCLUSIONS

A great deal of technology is available in the microwave acoustics, solid-state, integrated circuit, and microwave engineering disciplines which bear on the problems just enumerated. For example, the microwave acoustic technology provides a great deal of information on the deposition of piezoelectric films and low-loss substrates. The solid-state discipline has perfected the epitaxial deposition of semiconducting materials by the vapor transport, vacuum, and sputter deposition techniques. The analytic techniques of microwave engineering associated with electromagnetic waveguides and transmission lines and with couplers, matching networks, terminations, transitions, radiators, and the like could be applied to the design of their acoustic analogs.

In conclusion, the utilization of acoustic analogs of microwave circuits and concepts can provide components and circuits with substantially greater signal and data processing capacity than is now available. These components and circuits utilize well-known and well-understood physical properties of materials and interactions in these materials. A good deal of the necessary technology for the realization of these circuits and components is currently available in somewhat different form in allied disciplines. A relatively modest effort is required to bend this technology toward the realization of microsound components and circuitry.

These components have considerable advantages over bulk wave devices because they can be used to perform signal processing functions that are virtually impossible with bulk waves. Although electromagnetic microwave circuits can perform the same functions as microsound circuits, their great size (one square kilometer is equivalent to one square centimeter of microsound circuitry), high losses, and high cost make the microsound approach more attractive.

REFERENCES

1. H. Van Der Vaart and R. Damon, 1967 G-MTT Symposium Proceedings, 8 May 1967, Boston, p. 206.

2. M. B. Shultz, M. G. Holland and L. Davis, Jr., Appl. Phys. Letters 11, 237 (1967).

3. G. P. Rodrique, Proc. IEEE 53, 1428 (1965).

4. G. A. Coquin and R. Tsu, Proc. IEEE 53, 581 (1965).

5. J. H. McFee, Physical Acoustics, Vol. 4, Part A, ed. W. Mason (Academic Press, New York, 1966).

6. Lord Rayleigh, London Math. Soc. Proc. 17, 4 (1885).

7. I. A. Viktorov, Rayleigh and Lamb Waves: Physical Theory and Applications (Plenum Press, New York, 1967).

8. G. A. Coquin and H. F. Tiersten, 1966 Sonics and Ultrasonics Symposium, 12 October 1966, Cleveland, Paper N-6.

9. B. A. Auld, J. H. Collins and H. J. Shaw, 1968 Sonics and Ultrasonics Symposium, 25 September 1968, New York, Paper A-2.

10. D. B. Armstrong, 1968 Sonics and Ultrasonics Symposium, 25 September 1968, New York, Paper A-3.

11. E. A. Ash, 1967 G-MTT Symposium Proceedings, 8 May 1967, Boston, p. 194.

12. D. L. White, 1967 Sonics and Ultrasonics Symposium, 6 October 1967, Vancouver, Paper N-1.

13. H. F. Tiersten, Bell Telephone Laboratories, private communication.

14. E. A. Ash and D. Morgan, Electronics Letters 3, 462 (1967).

15. A. R. Hutson, J. H. McFee and D. L. White, Phys. Rev. Letters 7, 237 (1961).

16. R. M. White and F. W. Voltmer, Appl. Phys. Letters 8, 40 (1966).

17. H. Mathews and R. C. LeCraw, Phys. Rev. Letters 8, 397 (1963).

18. W. Strauss, J. Appl. Phys. 36, 118 (1965).

19. R. M. White, IEEE Trans. Electron Devices ED-14, 181 (1967).

20. Yu. V. Gulyaev and V. I. Pustovoit, Soviet Phys. JETP 20, 1508 (1965).

21. K. A. Ingebrigtsen, ELAB Report TE-94, The Norwegian Institute of Technology, Trondheim, Norway, November 1967.

22. J. H. Collins, private communication.

23. H. Engan, ELAB Report TE-91, The Norwegian Institute of Technology, Trondheim, Norway, September 1967.

24. Suggested by Theodore Bially.

25. J. Blass, IRE International Convention Record, Vol. 8, Part 1 (1960), p. 48.

26. J. E. Mee, Appl. Phys. Letters 10, 289 (1967).

27. J. J. Campbell and W. R. Jones, Hughes Aircraft Co., Fullerton, California, TP 68-14-7, 16 February 1968.

28. A. N. Broers, Microelectronics and Reliability 4, 103 (1965).

DOCUMENT CONTROL DATA - R&D		
(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)		

1. ORIGINATING ACTIVITY *(Corporate author)*	2a. REPORT SECURITY CLASSIFICATION
Lincoln Laboratory, M.I.T.	Unclassified
	2b. GROUP None

3. REPORT TITLE

Microsound Components, Circuits, and Applications

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*
Technical Note

5. AUTHOR(S) *(Last name, first name, initial)*

Stern, Ernest

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
30 October 1968	22	28

8a. CONTRACT OR GRANT NO. AF 19(628)-5167	9a. ORIGINATOR'S REPORT NUMBER(S)
b. PROJECT NO. ARPA Order 600	Technical Note 1968-36
c.	9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*
d.	ESD-TR-68-327

10. AVAILABILITY/LIMITATION NOTICES

This document has been approved for public release and sale; its distribution is unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
None	Air Force Systems Command, USAF

13. ABSTRACT

Acoustic analogs of conventional microwave transmission line (microsound) components on the surface of crystalline substrates should find application in wideband, high-capacity signal and data processors.

These microsound transmission lines, hybrids, and couplers interconnect microsound transducers, amplifiers, isolators, and phase shifters to form microsound circuits capable of autocorrelation, Fourier transformation, and matrix permutation functions.

Compatible component configurations are proposed and evaluated which perform the basic functions of wave guidance, amplification, isolation, and transduction. The anticipated difficulties with their realization is discussed, and the status of critical problems, including the epitaxial growth of acoustic thin films and sub-micron etching procedures, will be given. Several circuits capable of autocorrelation, cross correlation, Fourier transformation, and matrix permutation are described.

14. KEY WORDS

microsound components
microsound circuits
wideband acoustic phenomena
signal and data processing systems